Summary of the 3rd International Radio Occultation Workshop

Held in Seggau Castle, Leibnitz near Graz, Austria

From Thursday, 5th of September to Wednesday, 11th of September 2013

Starting at 09:15 hours on 5th of September

Ending at 14:30 hours on 11th of September

Executive Summary

Radio occultation (RO) data has a major positive impact on Numerical Weather Prediction (NWP), climate monitoring, space weather, and on temperature- and humidity-related atmospheric research. All global assimilation centres are using RO data to derive information on stratospheric temperature, and tropospheric temperature and humidity. In addition, the bias free nature of RO data anchors assimilation models to the true atmospheric state.

Recent NWP studies have shown substantial forecasting improvements with increased number of available occultations. Climate, research users also benefit from more data. The current observing system is providing about 3,000 occultations daily, relying however for more than half of the data on research type missions. The main recommendations from IROWG-3 are thus:

- Develop a detailed **GNSS-RO Continuity Plan**, outlining how we move towards a fully operational GNSS RO constellation providing **at least 10,000 observations per day**.
- Take steps to ensure **the continuity of RO measurements**, especially after COSMIC-1. **Operational GNSS RO missions are not only important for weather forecasting, but also for continuous global climate observation**.
- To ensure wherever possible a timely **update of receiver firmware** in order to maximise the receiver performance, e.g. for the Oceansat-2/ROSA instrument to allow L2 tracking, or for the GRAS instrument to extend the covered altitude range to 120 km.
- **Avoid an observation gap at mid- and high latitudes** by funding/launching the FORMOSAT-7/COSMIC-2 Polar mission[1].
- International space agencies (e.g., NASA, ESA, NSF, NOAA, EUMETSAT and others) to hold an **interagency workshop to define cooperation options for implementing an airborne demonstration and a LEO-LEO research and demonstration mission**.

[1] Based on the outcome of this IROWG workshop, a letter was sent by WMO to the United States to highlight the impact of RO data and the importance of implementing both, equatorial and polar constellations of FORMOSAT-7/COSMIC-2. In their response, the USA ensured WMO that NOAA was “coordinating on program planning and investigating options for acquisition of the second six mission payloads and launch services for the second launch”.

1 INTRODUCTION

This IROWG report presents the minutes / full recommendations of the combined OPAC-IROWG Workshop (OPAC-5 & IROWG-3) of the International Radio Occultation (RO) Working Group and the Occultation for Probing Atmosphere and Climate. The workshop was organized by the Wegener Center for Climate and Global Change at the University of Graz, Austria. The meeting was held at Seggau Castle, Leibnitz near Graz, Austria, from the 5th of September 2013 to the 11th of September 2013.

Background: The CGMS meeting 37 in October 2009 endorsed the establishment of the IROWG. Dave Ector (formerly NOAA, now UCAR) and Axel von Engeln (EUMETSAT) were selected as co-chairs and Mitch Goldberg (NOAA) as rapporteur to CGMS (Mitch was replaced in June 2012 by Anthony Mannucci, JPL/NASA). The first IROWG workshop was held in September 2010, it was a joint OPAC-4 and GRAS-SAF Climate workshop. IROWG-1 was "only" providing a platform for discussions and recommendations, while the talks that were given were organized by OPAC-4 and the GRAS SAF. The 2nd and 3rd workshops of IROWG included a full conference agenda with many talks, in addition to the platform for discussions and recommendations. Please refer to our website at http://www.irowg.org for minutes and working papers of previous workshops.

OPAC-5 & IROWG-3 was attended by more than 70 scientists, including representatives from all the major RO processing centres and all major weather prediction centres assimilating RO data. Approximately 60 talks and 25 posters were presented. Recommendations were developed in dedicated sub-working groups and presented in a panel discussion. Additionally, OPAC-5 & IROWG-3 were used by several researchers for dedicated splinter meetings, which are not covered here.

The structure of this report is as follows: Section 2 gives a brief overview of the organization of the workshop and the sub-groups, Section 3 lists the main recommendations which were agreed upon by IROWG, Section 4 contains the proceedings of the sub-groups, and Section 5 concludes.

This IROWG document provides the full minutes / recommendations / discussions of the sub-working groups within IROWG. Note that a summary of these minutes, and the main recommendations are going to be presented to CGMS-42 in a dedicated working paper and then made available at http://www.irowg.org.

Furthermore, there have been 2 additional documents provided by IROWG:

- Critical Impact of the Potential Delay or Descoping of the COSMIC-2/FORMOSAT-7 Programme, IROWG/DOC/2013/01
- Status of the Global Observing System for Radio Occultation (Update 2013), IROWG/DOC/2013/02

Both documents are available at http://www.irowg.org.

Both documents were triggered by the continuing uncertainty regarding the follow-on mission to FORMOSAT-3/COSMIC-1 - FORMOSAT-7/COSMIC-2 - in particular the high latitude part of this constellation. This uncertainty also dominated the discussions and recommendations of several of the sub-working groups within IROWG-3.

2 IROWG-3 SETUP

OPAC5 & IROWG-3 was a full workshop, including presentations, posters and sub-group discussions. Both, the presentations/posters and the sub-group discussions were focussed on specific topics, namely:

- Numerical Weather Prediction;
- Climate;
- Receiver Technology and Innovative Occultation Techniques;
- Space Weather.

In contrast to earlier workshops, the sub-group Research to Operations was **not** formed. This is a major policy shift of IROWG, resulting directly from the continuous non-delivery or under-performing of most research missions. The core of a sustainable RO observation system needs to be operational! The earlier separate sub-groups of Receiver Technology and Innovative Occultation Techniques were combined here.

IROWG-3 participants were asked to summarize **relevant activities** within the scope of the sub-group in dedicated meetings and express recommendations which could either be relevant to CGMS, to the GNSS (Global Navigation Satellite System, e.g. GPS) RO community, to providers of RO data, or within the IROWG. These were discussed in the open plenary.

3 IROWG-3 MAIN RECOMMENDATIONS

These will also be captured in the CGMS-42 working paper

OPAC-5 & IROWG-3 participants noted that the main IROWG-2 recommendations have made some progress; however, further work is required to address them fully. The urgency of the tasks requires that several of them be re-stated here in an updated form. In addition, the continuing uncertainty of the FORMOSAT-7/COSMIC-2 mission dominated the discussions and recommendations.

The following 5 main recommendations have been agreed upon by all participants at IROWG-3:

3.1 Ensure an Operational Continuity Plan for RO – including Troposphere and Ionosphere Measurements

We recommend that CGMS devise a detailed **GNSS-RO Continuity Plan** with the operational agencies, outlining how we move towards a fully operational GNSS RO constellation providing **at least 10,000 observations per day**.

GNSS RO has been demonstrated to be a critical element in the global data observing system for Numerical Weather Prediction (NWP), providing high positive impact to forecast skill in all the major national weather forecasting centres. GNSS RO also provides a very important data record for the global climate observing system, providing essential climate variables of benchmark quality. In addition, these data are critical for space weather observation and input to space weather prediction systems that are currently being developed.

The **continuity of GNSS RO observations in the future is not guaranteed by present operational programs or plans**. As of 2013, the two GRAS instruments remain the only program for GNSS RO with confirmed funding. The operational demonstration COSMIC-1/FORMOSAT-3 mission provided the first GNSS RO data used by the operational centres. However, COSMIC-1 is beyond its expected end of life. Research missions underperform or do not deliver any data. Two research satellites providing timely data suitable for assimilation are the GRACE and TerraSAR-X missions, but these missions combined provide less than one fifth of the data volume that COSMIC-1 provides. If COSMIC-1 fails before a COSMIC-2/ FORMOSAT-7 mission, an **observation gap at low latitudes** will occur. A **mid- and high-latitude gap with even longer duration** will also occur after COSMIC-1, unless the polar part of the COSMIC-2 mission is funded and executed.

Thus, **research programs or missions of opportunity are not the answer for a fully operational GNSS RO constellation that serves the needs of Numerical Weather Prediction centres**. The amount of investment in GNSS RO and other satellite programs overall should be correlated to the positive impacts they have on NWP, climate, and chemistry, and GNSS RO impacts in NWP are comparable to that of the other major operational instruments. Proper GNSS RO continuity requires a constellation of properly spaced LEO satellites, providing a minimum of 10,000 soundings per day. **It is of highest importance for NWP, climate, and space weather to ensure the continuity of RO measurements**, especially following the COSMIC-1/FORMOSAT-3 constellation mission. The first part of the follow-on COSMIC-2/FORMOSAT-7 is a **low inclination** (24 degrees) mission that will provide an unprecedented density of low latitude coverage critically needed for tropical storms and space weather monitoring and prediction. It will, however**, not provide any of the mid- and high-latitude coverage** required for NWP, climate, and space weather at those latitudes. The second part of the COSMIC-2/FORMOSAT-7 is a constellation of six satellites in polar orbit and this part of the mission would contribute greatly to the need for mid- and high latitude coverage; however this part is not yet completely funded and is at risk.

3.2 Ensure the continuity of RO measurements, in particular after COSMIC-1

GNSS RO has been demonstrated to be a very important data record for the global climate observing system providing essential climate variables of benchmark quality. The continuity of global GNSS RO observations in the future is not guaranteed, particularly the full diurnal coverage provided by COSMIC-1, which is of major concern regarding the provision of continuous climate products. **It is of highest importance to ensure the continuity of RO measurements with global coverage**, especially after COSMIC-1. **Operational GNSS RO missions for continuous global climate observation with full diurnal coverage** need to be established. While research missions are a valuable component, experience has shown that operational missions are required as a backbone to ensure continuity of the data.

3.3 Ensure adequate firmware settings of existing GNSS RO firmware

IROWG recommends to the Italian Space Agency (ASI) that it provide an **update of the firmware** to the ROSA instrument onboard Oceansat-2, that will significantly improve L2 tracking to be comparable to that already achieved for the other ROSA-flying instruments onboard Mega-Tropiques and SAC-D. Furthermore, IROWG recommends to EUMETSAT to explore the feasibility of **modifying the firmware** in the GRAS RO instruments onboard Metop-A, B and C, so that the occultations are continued to at least an altitude of 120 km. This will permit better insights into ionospheric sporadic E-layer signatures, which may be responsible for loss of lock or other tracking errors even at altitudes below 80 km (e.g., if/when E-layers are tilted). Tracking to higher altitudes than 80 km could also help investigations into ionospheric correction improvements at high altitudes as well as help to diagnose possible small mean bending angle biases, which could be important for climate monitoring. Finally, more data at high altitudes can help dynamic error estimation in the operational processing of occultations and ease the identification of bad data due to scintillations/tracking errors in limited vertical intervals.

3.4 Ensure timely launch of the FORMOSAT-7/COSMIC-2 Polar mission

IROWG recommends that all reasonable effort be expended to launch the FORMOSAT-7/COSMIC-2 (FS7/C2) Polar mission in the 2018 time frame as originally planned. With the decline of FORMOSAT-3/COSMIC-1 and other research satellites, lack of FS7/C2 Polar will result in the absence of any ionospheric radio occultation measurements above approximately 40° latitude. FS7/C2 first launch is planned for a low inclination orbit that will not provide data at middle and higher latitudes, where significant space weather impacts are present, needing to be monitored.

3.5 Organize an international space agency workshop for cooperation options on airborne and LEO-LEO research missions

IROWG recommends that CGMS adopt an action asking international space agencies (NASA-ESA-NSF-NOAA-EUMETSAT and others) to **hold an interagency workshop** as soon as possible to define how they can cooperate in implementing an airborne demonstration and a LEO-LEO research and demonstration mission. IROWG also recommends that CGMS encourage space agencies to support research towards implementation of LEO-LEO occultation demonstration to pave the way towards developing an authoritative reference standard in the global free atmosphere for upper air WMO/GCOS Essential Climate Variables (ECVs). Initial mountaintop demonstrations have been made at cm, mm and micrometer wavelengths. The next step within the next 2 years should be an airborne occultation demonstration.

4 SUB-GROUP RECOMMENDATIONS / DISCUSSIONS

This section presents the recommendations, actions, and discussions from the different sub-groups. Note that sub-groups were asked for a few main recommendations, but were otherwise free to discuss and present all other relevant issues. Hence discussion form and presentation is not uniform throughout the different presentations. Actions were only allowed within the sub-groups or within IROWG with consent by the Actionee.

4.1 Numerical Weather Prediction (NWP) Sub-Group

Chair: Lidia Cucurull (NOAA, US)

Rapporteur: Josep M. Aparicio (EC, Canada)

Participants: Harald Anlauf (DWD, Germany), Richard Anthes (UCAR, US), Dave Ector (UCAR, US), Axel von Engeln (EUMETSAT, Europe), Sean Healy (ECMWF, Europe), Hataek Kwon (KIAPS, South Korea), Yan Liu (CMA, China), Johannes Nielsen (DMI, Denmark), Hiromi Owada (JMA, Japan), Nathalie Saint-Ramond (Meteo France, France), Bill Schreiner (UCAR, US), Marc Schwaerz (WEGC/U Graz, Austria), Hallgeir Wilhemsen (DMI, Denmark), Chris Burrows (UK Met Office, UK)

Background

We note that many of our recommendations have been carried forward again, some progress is noted. However, **failure to secure funding, so far, for GNSS constellations such as COSMIC-2 is received as a disappointment**. Investment in GNSS and satellite programs overall should be correlated to the positive impacts they have on NWP, climate, and atmospheric chemistry, in order to optimize the impact of the global observing system.

Recommendation to CGMS

1. We reaffirm previous statements (see earlier minutes as well as the Fifth WMO NWP Impact Workshop (Sedona, May 2012) report, where we quote the request for at least "10,000 occultations/day **from operational systems**" and that "GPSRO has become a critical component of the Earth Observation System"). It is our judgment, based on the success of COSMIC-1, that the only well-defined mission able to fill this operational role within the next 5 yrs is COSMIC-2 (for which funding is not yet complete). **Both, equatorial and polar components of COSMIC-2 are required for NWP**.
2. The 10,000 occultations/day **delivered in near real-time** (see Action below), **providing global coverage (i.e. uniformly distributed in latitude/longitude), profiling down through the lower troposphere, and covering all local times, is the recommended minimum requirement for an operational baseline** (i.e. attempts to fulfil an operational baseline should target to provide not less than that amount). Studies show that additional observations still improve forecast significantly, and there would still be significant additional benefit from at least doubling that number.
3. Current operational assimilation of GPS RO data is heavily dependent on research missions and research missions are ending their life. Previous hope that research missions would provide significant amounts of data have not materialized. Therefore it is our recommendation that the NWP community **should not divert significant amounts of effort** or expectations on these missions for operational purposes.

Actions within IROWG NWP Sub-Group

Action IROWG3-01: NWP sub-group will compile a table of current Metop-B standard latencies (50 and 90% latencies, after processing, ready for delivery). Future operational missions should take that table as standard requirement (incl. COSMIC-2).

Recommendations within IROWG

Recommendation: GFZ: Tandem-X rising data can be technically provided, if enough interest is shown. The potential amount of data is moderate, and GFZ is using the platform as a workbench. This community should discuss further if we proceed in this request (see Major conclusion 3).

Recommendation: Evaluation of the possibilities offered by FY3 (Chinese polar operational), as an operationally committed program should be considered. We encourage collaboration. Details, such as the Interface Control Document (ICD) should be provided ASAP for this evaluation.

Notes

- All participants having contributed to the evaluation of the non-operational data sources will prepare a draft paper. The draft will be led by Harald Anlauf (DWD). This project will be reviewed by December 2013, if it is still appropriate to follow.
- New BUFR content: Bill Schreiner will (around Nov 2013) send some sample data (worth 2 months) to check contents and verify if there is any problem, and any added value. Data is supposed to be statistically equivalent to present format, with enhanced resolution in the low atmosphere. After verification, if useful, and after iteration, it will be proposed as the new content to be produced by CDAAC. The new content should be compatible in WMO format.
- Data providers should compare technical details of the contents of their deliverables, and identify any disagreement in their meaning. In the longer term, the BUFR format should be updated, providing more accurate parameter definitions. Meanwhile, speak with Dave Offiler (UK Met Office) about the possibility of a tighter specification. Specifically, the precise use of the following parameters has been identified as inconsistent or ambiguous:
  a. latitude, longitude, azimuth, azimuth direction,
  b. satellite positions and velocity (reference frames),
  c. reference time of the occultation,
  d. radius of curvature,
  e. geoid (JGM, EGM96, EGM2008).
- A technical solution that clarifies the parameter details will be requested from data providers. This can be a documented specification through software number or similar. Data providers shall document the specification of the chosen parameters for each processing release.
- Concerning Jason-CS on EUMETCast: These data will be available through GTS. Therefore, there is no need to add it to EUMETCast.
- The RO community should better express the likely future size and operational commitment of the ensemble of satellites. Standard presentations misleadingly suggest a large amount of data to be available over the next years. Many missions are research missions, unavailable in near real time or at all, at EOL, or of low performance (120 vs. 600 occultations/day).
- The UK Met compiled a table of several parameters. NWP centres should check that the info on the table is up to date and provide additional information, such as the cutoff times. Data providers should check how their delivery latencies compare against cutoffs times (cf. Action above).

4.2 Climate Sub-Group

Chair: Ulrich Foelsche (WEGC, Austria)

Rapporteur: Andrea Steiner (WEGC, Austria)

Members: Chi Ao (JPL, US, took notes), Riccardo Biondi (WEGC, Austria), Alejandro de la Torre (CONICET, Argentina), Hans Gleisner (DMI, Denmark), Vladimir Gubenko (RAS, Russia), Raimund Klingler (WEGC, Austria), Kent Lauritsen (DMI, Denmark), Panagiotis Vergados (JPL, US), Florian Zus (GFZ, Germany)

Visitors: Julia Danzer (WEGC, Austria), Rob Kursinski (Moog, US), Gottfried Kirchengast (WEGC, Austria), Florian Ladstädter (WEGC, Austria), Andreas Plach (WEGC, Austria), Axel von Engeln (EUMETSAT, Europe)

Recommendations to CGMS

1. GNSS RO has been demonstrated to be a very important data record for the global climate observing system providing essential climate variables of benchmark quality. The continuity of GNSS RO observations in the future is not sufficiently guaranteed, which is of main concern regarding the provision of continuous climate products. **It is of highest importance to ensure the continuity of RO measurements with global coverage**, especially after COSMIC-1. **Operational GNSS RO missions for continuous global climate observation** need to be established. While research missions are a valuable component, operational missions are required as a backbone to ensure continuity.
2. **Global coverage and coverage of all local times needs to be ensured for a climate observing system.** A monthly mean record utilizing the effective horizontal resolution of about 300 km with a 6-hour resolution of the diurnal cycle requires 20000 occultations per day.
   The current and future Metop satellite series only cover certain local times. The COSMIC-1 mission is rapidly declining and we are facing an imminent observational gap. A COSMIC-1 follow-on mission is needed urgently. The first satellites of the planned COSMIC-2 mission will be in low inclination orbits and will cover low latitudes only. Thus, for the future there is an urgent need for COSMIC-2 second satellites in high inclination orbits to provide global coverage and local time coverage. Overall, the aim should be to take advantage of all available GNSS constellations to maximize coverage.
3. **Promote cross-collaboration and sharing of data and knowledge between the RO community and the satellite operators**, e.g., the FY-3 satellite series with the GNOS receiver might be an important data contributor in the future. Making the raw data, level 1a phase and amplitude data, and orbit data available to the scientific community as soon as possible is regarded of high importance. Continuous collaboration and data comparison are of great value for all parties.
4. **Encourage software flexibility (especially upload) in future RO missions**.
5. **Promote and support reprocessing activities of RO climate data records** from different RO processing centers along the principles for re-Processing climate data

records of the WCRP Observation and Assimilation Panel (WOAP; http://www.wcrp-climate.org/documents/WOAP_ReprocessingPrinciples.pdf).

6. **Encourage NWP centers to engage in reanalysis activities based only on data types that are not bias-corrected, especially RO.** ECMWF, e.g., carries out such an activity as part of the ROM SAF CDOP-2 plans.

Recommendations to satellite operators and data providers

1. Documentation on retrieval processing chains by all processing centers is essential to ensure traceability in climate data (e.g., 1DVar retrieval documentation). Documentation on LEO receiver firmware is also needed. IROWG recommends **fully documenting processing chains, keeping track of any introduced changes/updates to processing or instrument**.
2. All level 1 data providers should **make available the raw data, level 1a phase and amplitude data, and orbit data in a standard format,** preferably NetCDF, as soon as possible. This would enable independent RO processing centers to cross-check their systems and to estimate the overall uncertainties in their retrievals (see recommendation #3 to CGMS above).
3. **RO measurements from ROSA receivers** on current missions (e.g., SAC-D, MEGHA-Tropiques) **need to be made available to the scientific community soon** in order to investigate the climate utility of ROSA data. These data could help to fill the gap after COSMIC-1 (see recommendation #3 to CGMS above).
4. Data providers should maintain parallel data streams of RO climate products, one operational and one uniformly reprocessed version.

Recommendations within IROWG

1. **The ROTrends and SCOPE-CM working groups should continue to contribute to the affirmation of GNSS RO as a climate monitoring system** by assessing the sensitivity of trends (1) to retrieval system and (2) to receiver provider.
2. There is an uncertainty in the refractivity coefficients that might impact the accuracy and stability of RO climate time series and trends. **There is need for new measurements of the refractivity coefficients with higher accuracy (better than 1.E-4).**
3. **Issues of ionospheric correction and statistical optimization should be further investigated to optimize the climate utility in the entire stratosphere.**
4. **Encourage research into the benefits of higher SNR**, which is likely to extend the benchmarking capability of GNSS RO more robustly into the troposphere and higher into the stratosphere.
5. Systematically investigate the **feasibility of an RO "climate-quality" water vapor** product.
6. **Continue participation in the wider scientific community** (e.g., CMIP, GEWEX, SPARC, ITWG) and collaboration for the promotion of RO data and the complementary use of different data sets.

7. Recent studies found a signature in L1/L2/L5 signals from Block IIF satellites, which could affect the quality of the RO benchmark climate record. **This L1/L2/L5 drift in recent Block IIF satellites as well as possible L1/L2 drift on previous Block I, Block II satellites needs to be investigated.**

8. Investigate the consistency of data from different RO missions ($2.0 \cdot 10^{-8}$ rad bending angle offset).

Action IROWG3-02: IROWG co-chairs to check progress towards updated laboratory measurements of the refractivity coefficients.

4.3 Receiver Technology and Innovative RO Techniques

Chair: R. Kursinski (Moog, US)

Rapporteur: S. Syndergaard (DMI, Denmark)

Participants: Johannes Fritzer (Wegener Center, Austria), Oliver Montenbruck (DLR, Germany), Erin Griggs (CU, US), Jens Wickert (GFZ, Germany), Dave Ector (UCAR, US), Gottfried Kirchengast (Wegener Centre, Austria), Kefei Zhang (RMIT, Australia), Congliang Liu (RMIT, Australia), Yago Andres (EUMETSAT, Europe), Alexander Pavelyev (RSSI, Russia), Riccardo Notarpietro (Politecnico die Turino, Italy), Pratik Dave (MS, US)

High priority recommendations

Ensuring adequate firmware settings of existing GNSS RO firmware

IROWG recommends to the Italian Space Agency (ASI) that it provide an **update of the firmware** to the ROSA instrument onboard Oceansat-2, that will significantly improve L2 tracking to be comparable to that already achieved for the other ROSA-flying instruments onboard Mega-Tropiques and SAC-D. Furthermore, IROWG recommends to EUMETSAT to explore the feasibility of **modifying the firmware** in the GRAS RO instruments onboard Metop-A, B and C, so that the occultations are continued to at least an altitude of 120 km. This will permit better insights into ionospheric sporadic E-layer signatures, which may be responsible for loss of lock or other tracking errors even at altitudes below 80 km (e.g., if/when E-layers are tilted). Tracking to higher altitudes than 80 km could also help investigations into ionospheric correction improvements at high altitudes as well as help to diagnose possible small mean bending angle biases, which could be important for climate monitoring. Finally, more data at high altitudes can help dynamic error estimation in the operational processing of occultations and ease the identification of bad data due to scintillations/tracking errors in limited vertical intervals.

Moving LEO-LEO occultation development forward towards a demonstration mission

IROWG recommends that CGMS adopt an action asking international space agencies (NASA-ESA-NSF-NOAA-EUMETSAT and others) to **hold an interagency workshop** as soon as possible to define how they can cooperate in implementing an airborne demonstration and a LEO-LEO research and demonstration mission. IROWG also recommends that CGMS encourage space agencies to support research towards implementation of LEO-LEO occultation demonstration to pave the way towards developing an authoritative reference standard in the global free atmosphere for upper air WMO/GCOS Essential Climate Variables (ECVs). Initial mountaintop demonstrations have been made at cm, mm and micrometer wavelengths. The next step within the next 2 years should be an airborne occultation demonstration.

GNSS system recommendations

Transmitter system: General recommendations

1. IROWG acknowledges the release of the B1 Open Service ICD for BeiDou. IROWG recommends to China to make BeiDou/Compass ICDs with full required information (i.e., including B2 and B3 signals) available so that future missions can make use of the signals from this Navigation System, increasing the number and usefulness of RO measurements for both NWP and climate.
2. IROWG recommends to the Indian Space Research Organization to make a comprehensive IRNSS signal ICD available so that future missions can make use of the signals from this Navigation System, increasing the number and usefulness of RO measurements for both NWP and climate.
3. IROWG recommends to operational agencies and instrument developers to also consider the use of GLONASS FDMA as well as the new and emerging constellations (BeiDou, Galileo, IRNSS, QZSS) in future receivers, in order to increase the number of available RO measurements.
4. IROWG recommends closer cooperation between the RO community and organizations such as IGS (International GNSS Service) and GNSS system operators by, e.g., participation in its organizing bodies / governing board.
5. IROWG recommends that the GNSS constellation operators provide Equivalent Isotropically Radiated Power (EIRP) as a function of the on-board antenna angles (elevation and azimuth) on a satellite per satellite basis, formed from post-launch power measurements combined with transmit antenna gain patterns.
6. IROWG recommends that the GNSS satellites transmit significant power levels beyond the limb of the earth, in order to allow radio occultation applications from LEO meteorological satellites.

Transmitter system: Modulation on new GNSS signals, desire for un-modulated pilot tones

Rationale: In the not too distant future there will be 6 international GNSS constellations: GPS, GLONASS, Galileo, BeiDou, QZSS, and IRNSS. With 12 orbiting LEO satellites, these will produce more than 30,000 daily occultations.

The navigation modulation of new GNSS signals and systems is yielding increasing precise ranging data. Unfortunately this modulation makes it increasingly difficult to use these signals for open loop tracking in the lower troposphere and will likely degrade occultation performance there. The new navigation modulation such as binary offset carrier (BOC) has a more complex autocorrelation function that not only narrows the central peak of the autocorrelation function but also has anti-correlated response at certain time lags. This response makes acquisition of signals in the lower troposphere difficult and will at the very least degrade the occultation performance there and may render the new signals unusable for occultations in the lower troposphere.

Recommendations: We recommend that CGMS

- **Make GNSS developers aware of the important NWP and climate applications of their GNSS systems and how the GNSS signals and systems are being used**
- **Encourage space agencies to maintain course resolution (BPSK) modulation signals**
- **Consider transmitting un-modulated pilot carrier tones for occultations for NWP and climate.**

Transmitter system: Additional signals on GNSS (e.g. 5 GHz on Galileo)

Rationale: Current GNSS systems use L-band frequencies between 1 and 2 GHz. Additional use of one or more higher frequencies well separated from L-band would have substantial benefit to RO. For instance, for Galileo, ESA is considering a 5 GHz frequency in the C-band range. This would increase the useful altitude range of GNSS radio occultation by about 15 km because sensitivity to the ionosphere is an order of magnitude less at 5 GHz than at L-band frequencies. Ionospheric scintillations induced by sporadic E-layers, which can influence the accuracy of retrieved profiles in the stratosphere, will be significantly reduced at 5 GHz. In addition, such signals would open the door to new applications of RO signals that exploit the better sensitivity to depolarization and reflection effects in C-band such as remote sensing of precipitation, capillary wave/gravity wave interactions and surface winds over oceans. Focus in this area should be given to signal modulation/coding schemes that reduce interference by other signals, improve range resolution and increase SNR.

Recommendation: We recommend that CGMS **encourage space agencies to assess the utility of higher frequencies on next generation GNSS systems** (e.g., 5 GHz on a next generation Galileo) for radio occultation and related applications. In this context, CGMS is also invited to encourage GNSS providers (Galileo, GPS, GLONASS, COMPASS, and IRNSS) to consider implementation of such higher frequencies for the benefit of operational weather and climate monitoring and prediction.

Payload recommendations

Receiver system: General recommendations

1. IROWG recommends that missions, instrument developers, and RO data processing centres provide level0 data format documentation, and/or necessary software to read data, and payload firmware configuration information.
2. IROWG recommends that an investigation of the GNSS transmitter frequency variations over temperature for durations of a few minutes that can affect un-differenced or single- differenced occultation observations is performed.
3. IROWG recommends that the GNSS RO payload manufacturers publish / make available how the observations are formed.
4. IROWG recommends that the GNSS RO manufacturers and RO data users work together to identify sources of RFI that affect RO observations.
5. IROWG recommends that JPL and GFZ determine the feasibility of modifying the firmware in the IGOR RO instruments on TDX and TSX. Firmware modifications should include at least the following three features:

1) If not already in place; load the most up to date and capable firmware version on both instruments.
2) Test L2C setting occultations on both with the expectation that L2C occultations will be permanently enabled on both TDX and TSX.
3) Add capability to output 100 Hz RO phase and SNR on one unit and compare TDX with TSX running at both 50 Hz and 100 Hz rates.

6. Given the large uncertainty in the time of availability of the future signals, IROWG recommends maintaining a proper flexibility in the design of future GNSS-RO receivers. Joint support of L1/E1, L2 (P(Y) and L2C), and L5/E5a is recommended to enable dual-frequency tracking of GPS, QZSS and Galileo.
7. IROWG recommends to the Italian Space Agency (ASI) to ensure the update of the firmware to the ROSA instrument onboard Oceansat-2, so that L2 tracking is significantly improved as is the case already for the other ROSA-flying instruments onboard Mega-Tropique and SAC-D.
8. IROWG recommends EUMETSAT to explore the feasibility of modifying the firmware in the GRAS RO instruments onboard Metop-A, B and C, so that the occultations are continued to at least an altitude of 120 km, to permit insights into the E layer signatures.

4.4 Space Weather Sub-Group

Chair: P.R. Straus (The Aerospace Cooperation, US)

Rapporteur: A. J. Mannucci (JPL, US)

Members: J. Y. Liu (NCU, Taiwan), Weihua Bai (NSSC, China), Jerome Lafeuille (WMO, Switzerland), Ho-Fang Tsai (NCU, Taiwan), Xianyi Wang (NSSC, China), Xiaocheng Wu (NSSC, China), Sun Yue-Qiang (NSSC, China)

Recommendation to CGMS

1. **The Space Weather Group of IROWG recommends that all reasonable effort be expended to launch the FORMOSAT-7/COSMIC-2 (FS7/C2) Polar mission** in the 2018 time frame as originally planned. With the decline of FORMOSAT-3/COSMIC-1 and other research satellites, lack of FS7/C2 Polar will result in the absence of any ionospheric radio occultation measurements above approximately 40° latitude. We note that FS7/C2 first launch is planned for a low inclination orbit that will not provide data at middle and higher latitudes, where significant space weather impacts are present, needing to be monitored.
2. **The Space Weather Group of IROWG recommends that an International Workshop be held to discuss three aspects of RO analysis involving the ionosphere,** probably to be funded by government agencies. The workshop should include a cross-section of ionospheric space weather experts and scientists concerned with removing ionospheric effects from RO for neutral atmospheric parameters. The workshop will include the following four sessions: (A) removing ionospheric effects from RO for neutral atmospheric parameters; discussion of various ionospheric corrections currently being used; (B) discussion of various ionospheric data assimilation methods; (C) ionospheric effects, especially scintillation, on Radio Occultation using the extensive RO databases; (D) extending atmospheric

measurements to 40-90 km altitude range to improve characterization of lower-upper atmosphere coupling (See Notes section for additional information regarding workshop discussion at IROWG-3).

3. **IROWG recommends that CGMS encourage international support of the FORMOSAT-7/COSMIC-2 program through the fielding of FS7/C2 ground stations in countries at low latitudes to augment ground stations planned by the USA and Taiwan.** This action will significantly reduce the data latency from FS7/C2 in the important low latitude and equatorial regions. Of particular interest is the development of three latitudinal chains of three ground stations each in the Asian, Middle Eastern/African, and American longitude sectors. It is recognized that a first step is to obtain configuration and access information for FS7/C2 ground stations distributed globally. (See Action IROWG3-02).

4. The lack of ionospheric RO data is becoming a limiting factor in the inversion of RO data from the lower atmosphere. In addition, the value of GNSS RO data to ionospheric modeling is expected to grow as the amount of available data increases over time. A variety of science and operational missions are in the planning stages, and it seems likely that more may be planned in the near future. While GNSS RO sensors that are able to observe lower atmospheric profiles can also generally measure ionospheric RO signals, there have been times in the past (e.g., GRAS on METOP) when the focus on terrestrial retrievals has resulted in unnecessary exclusion or reduction of ionospheric capability. Furthermore, GNSS RO sensor capabilities for observing ionospheric scintillation are not yet common to all missions. In addition, low data latency needs associated with operational space weather applications are not always met. **IROWG recommends CGMS to encourage missions flying GNSS RO sensors to incorporate a complete set of ionospheric measurements including measurements of ionospheric scintillation (high rate data scintillation measurements on all available line of sight TEC measurements) and, wherever possible, to reduce data latencies to less than 30 minutes**. It should be noted that antenna designs similar to COSMIC-1 (wherein canted zenith antennas with broad fields of view are used for tracking ionospheric occultations) provide one means of maximizing ionospheric data collection.

5. GNSS RO has been demonstrated to show great value in the global ionospheric climate, weather, variability monitoring and related scientific research. This value is expected to be greatly increased with more available data over time. However, the RO data format, a system for real time data access, and a historical data archive for ionospheric data is not yet established. **IROWG recommends that CGMS coordinate efforts to standardize an ionospheric data format for operational use of RO (similar to the BUFR format in the neutral atmosphere), create a real-time data accessing service available for space weather assimilation models, and archive historical data for ionospheric climate and scientific research purposes.** This will especially benefit operational nowcast and short term forecast space weather capabilities.

Recommendations within IROWG

1. In its response to action 39.03 received from CGMS regarding development of an inventory of radio occultation missions, **IROWG should incorporate the abilities of each mission to obtain ionospheric data so as to highlight the compliance, or lack**

thereof, of each mission with the Main Recommendation #3 above. The information in the inventory for each RO mission should include the extent to which the mission collects ionospheric profile data, the data latency associated with the mission, and the extent to which ionospheric scintillation data are collected.

2. The coupling between stratosphere/mesosphere/lower thermosphere and the ionosphere through gravity waves, planetary waves, and tides has shown significant and unexpected contributions to ionospheric variability. GNSS RO provides unique observations to conduct related scientific research by simultaneously sampling both the lower atmosphere and ionosphere. However, the currently processed RO data has a gap between ~40 and 90 km due to the difficulty of completely removing the ionospheric effects on the ray bending caused in the neutral atmosphere. **IROWG recommends efforts to develop improved analysis methods and instrumentation to extend the upper altitudes of current RO retrieval capability, starting with a focus group at the international workshop recommended in CGMS action #2.**

Recommendations within Sub-Group

1. It is desirable to continue to expand the sub-group membership in the areas of personnel associated with operational space weather support centers and members of the international science community involved in the development and evaluation of assimilative ionospheric and scintillation models. Team members should advocate for travel support from operational space weather support centers that will enable scientists to support future IROWG meetings.
2. Space Weather sub-group team members should continue to advocate for and support greater incorporation of ionospheric radio occultation science topics (such as those described in CGMS Recommendation #2) within existing ionospheric science venues such as CEDAR (leads: Geoff Crowley & Gary Bust) and IRI workshops (leads: J. Y. (Tiger) Liu and S. Y. Su). Collaborations within the sub-group membership involving evaluations of ionospheric models using GNSS RO data, or development/refinement of ionospheric or scintillation specification models using GNSS RO data sets, are also encouraged.
3. Advancement of ionospheric model science depends on collection of both ionospheric electron density information, such as is obtained from GNSS RO sensors, and coincident observations of thermospheric parameters such as neutral composition and winds, and ionospheric plasma drifts. Since it is unlikely that the ultimate solution to ionospheric specification problems can be accomplished with GNSS RO observations alone, the members of the Space Weather sub-group should engage with the COSMIC-2 program to advocate for incorporation of space weather secondary payloads on the high inclination portion of that mission.
4. The sub-group should coordinate with space weather activities throughout WMO. **A member of the WMO ITCSW should make an attempt to attend future IROWG Space Weather sub-group meetings.**

Action IROWG3-03: J. Y. Liu and Tony Mannucci will each provide a report on the activities at CEDAR that were initiated by Gary Bust and Geoff Crowley as part of Action IROWG2-08. J. Y. Liu will report RO related activities at the IRI conference in Olsztyn, Poland (June 2013). Due: IROWG-4.

Action IROWG3-04: Obtain information regarding access to COSMIC-2 data downlinks globally to decrease data latency (objective is 30 minutes or less). Tony Mannucci will contact Paul Straus of Aerospace Corp to obtain information from the USAF. J. Y. Liu will contact NSPO to obtain information from that organization. Due: IROWG-4.

Action IROWG3-05: Sun Yue-Qiang of the Space Weather Sub-group will provide information on the planned use of FY-3C ionospheric data, including its use in space weather models. Due: IROWG-4.

Action IROWG3-06: All IROWG members to check and to provide feedback on the information given in the WMO Observing Systems Capability Analysis and Review Tool OSCAR: http://www.wmo-sat.info/oscar/. Due: ongoing.

Discussion at IROWG-3

A task force will be formed to organize the workshop (see recommendation No 2 to CGMS above). The location will be at the next COSMIC-1/FORMOSAT-3 Data User's Workshop in Boulder, CO planned for 2014.

J. Y. (Tiger) Liu will attend the Third Space Weather Meeting planned for China in November 2013 and will present radio occultation related science topics. He will report on the meeting at IROWG-4.

To support Recommendation #5 to CGMS on a common data format for ionospheric radio occultation data, Jerome Lafeuille (WMO) will contact Terry Onsager (NOAA) and Bill Schreiner (UCAR) to coordinate format development. Terry will help coordinate this through WMO ICTSW (ISES – space environment service – has an activity to define formats). UCAR can inventory existing instrument formats to determine best approach.

Jerome Lafeuille will investigate GRACE and CHAMP data records in the WMO OSCAR database as regards ionospheric occultation capability.

J. Y. Liu will send contact information regarding Japanese satellite GAIA-1, 2017 launch which is a potential ionospheric radio occultation mission.

New RO capability inventory planned as part of CGMS-41 actions should include ionospheric capabilities separately from the neutral atmosphere capabilities.

Chinese members are encouraged to lead a workshop in China related to RO missions and space weather and report back to IROWG.

We might consider the next steps to make available short-term ionospheric forecasts widely available. J. Y. Liu's group is currently conducting data assimilation research with the NCAR HAO TIEGCM model. NOAA has USTEC right now. A real-time version of IRI (IRTAM) with assimilation capabilities is being developed at Goddard (D. Bilitza). J. Y. Liu has sent a student to Goddard to improve the IRI topside using FORMOSAT-7/COSMIC-2 data.

Notes

Additional information regarding the first IROWG recommendation #2 for workshops is as follows:

Session A) Space weather (ionosphere) has a potentially significant impact on the operational use of radio occultation by introducing biases in the neutral atmospheric retrieval products that are routinely assimilated. Considerable ionospheric space weather expertise exists that could benefit the neutral atmosphere community to mitigate these impacts. Yet, this expertise is not integrated into the research and operations communities that assimilate RO data. **We recommend that a working group (WG) be formed over the next 18 months to organize and conduct a workshop supported by the WMO and other operational agencies that brings together a cross-section of ionospheric space weather experts and the neutral atmosphere community.** The WG will discuss the various ionospheric corrections currently being applied and possible improvements. Areas to be discussed include solar cycle, diurnal and seasonal variability, and sporadic-E climatologies. The extensive RO databases that currently exist are a valuable resource.

Session B) RO is not yet fully utilized by the operational space weather communities that are focused on ionospheric specification and nowcast. **We further recommend the formation of a focus group with support from operational agencies to develop uniform metrics for evaluating assimilative ionospheric models that ingest RO data, and to advance modeling approaches for assimilating RO data for space weather nowcasts and forecasts.**

Session C) An emerging use of RO is to measure L-band scintillation caused by ionospheric irregularities, from space. There is currently insufficient knowledge of how L-band scintillation measurements acquired in an occultation geometry translate to other geometries and frequencies of interest. **We recommend the formation of a focus group with support from operational agencies to address how space-based scintillation measurements can be used operationally.** A goal of the group is to understand how measurements from space can be compared to the extensive databases and models of scintillation developed from ground-based measurements. This should include a discussion of recommended flight receiver designs, acquisition approaches, algorithms for flight and ground processing of scintillation parameters, and the use of RO data for scintillation products.

Session D) The coupling between stratosphere/mesosphere/lower thermosphere and the ionosphere through gravity waves, planetary waves, and tides has shown significant and unexpected contributions to ionospheric variability. GNSS RO provides unique observations to conduct related scientific research by simultaneously sampling both the lower atmosphere and ionosphere. However, the currently processed RO data has a gap between ~40 and 90 km due to the difficulty of completely removing the ionospheric effects on the ray bending caused in the neutral atmosphere. **We recommend the formation of a focus group to develop improved analysis methods and instrumentation to extend the upper altitudes of current RO retrieval capability and to develop methods of validating these high altitude measurements.**

5 CONCLUSIONS

The full set of recommendations - relevant at CGMS, at satellite operator, and at IROWG level - of the third IROWG meeting were summarised above, including further discussion / background material.

Concerning recommendations for work in the immediate future the following recommendations are emphasised:

- Develop a detailed **GNSS-RO Continuity Plan**, outlining how we move towards a fully operational GNSS RO constellation providing **at least 10000 observations per day**.
- Take steps to ensure **the continuity of RO measurements**, especially after COSMIC-1. **Operational GNSS RO missions are not only important for weather forecasting, but also for continuous global climate observation**.
- To ensure wherever possible a timely **update of receiver firmware** in order to maximise the receiver performance, e.g. for the Oceansat-2/ROSA instrument to allow L2 tracking, or for the GRAS instrument to extend the covered altitude range to 120 km.
- **Avoid an observation gap at mid- and high latitudes** by funding/launching the FORMOSAT-7/COSMIC-2 Polar mission[2].
- International space agencies (e.g., NASA, ESA, NSF, NOAA, EUMETSAT and others) to hold an **interagency workshop to define cooperation options for implementing an airborne demonstration and a LEO-LEO research and demonstration mission**.

All given presentations and posters at OPAC-5 & IROWG-3 are available at http://www.uni-graz.at/opacirowg2013/, other documents from this workshop are available at http://www.irowg.org.

ACKNOWLEGEMENTS

The sponsors of the OPAC-5 & IROWG-3 workshop are available at the main workshop website at http://www.uni-graz.at/opacirowg2013/.

ACTIONS

The actions from the IROWG-2 workshop (28th March - 3rd April 2012), including their status, are collected below.

Action IROWG2-01: On IROWG co-chairs to contact the ITWG and survey the common	**Open:** Email has been sent to contact M. Goldberg, N. Bormann of ITWG, options

[2] Based on the outcome of this IROWG workshop, a letter was sent by WMO to the United States to highlight the impact of RO data and the importance of implementing both, equatorial and polar constellations of FORMOSAT-7/ COSMIC-2. In their response, the USA ensured WMO that NOAA was "coordinating on program planning and investigating options for acquisition of the second six mission payloads and launch services for the second launch".

interests between the groups.	for closer contact are being evaluated. Contacted several IROWG scientists on whether they are participating in the ITWG 2015 conference.
Action IROWG2-02: Josep Aparicio will undertake a review to estimate both the total number of radio occultation measurements and the number of operational measurements available per day, based upon the current timeline of GNSS. This will allow us to foresee problems in data coverage in the coming years. An example is the data gap between COSMIC-1 and COSMIC-2; as there is a distinct possibility of no COSMIC-1 data by 2014.	**Open:** Historical and estimated data volumes will be closed with a report to be distributed during January 2014.
Action IROWG2-03: Chris Burrows and Ben Ruston will distribute a survey between operational centres showing use of GPS data, thinning methods, bending angle and/or refractivity use, observation error, and observation sensitivity plots.	**Closed.** The survey has been completed and is currently being updated to include cutoff information from the NWP centers. The updated results will be linked from the IROWG website in January 2014.
Action IROWG2-04: NRL, ECMWF, JMA and EC; and if possible DWD, NCEP, Météo-France and UK Met Office will conduct a data denial experiment which uses only GRAS for a time period for a minimum of a month. Josep Aparicio, Sean Healy and Ben Ruston will coordinate the time of the case study (likely 2010) and coordinate the experiment with the other centres. We will include the observation sensitivities from each of the centres.	**Closed.** Summary was presented at IROWG-3, a summary of the results is being prepared and will be made available at least through http://www.irowg.org.
Action IROWG2-05: On IROWG co-chairs and B. Ho, A. Steiner: Provide the following ROTrends information on the IROWG homepage: (a) Links to processing descriptions of all data providers; (b) Published ROTrends intercomparison papers; (c) ROTrends PPC and MMC datasets (including sampling errors of the latter).	**Open:** Work is currently ongoing to update the IROWG website with a dedicated Project tab.
Action IROWG2-06: F. Zus to check availability of level 0 data of TerraSAR-X in Near-Real-Time.	**Closed:** Level 0 data of TerraSAR-X will not be available in Near-Real-Time. It is available offline though.
Action IROWG2-07: Gottfried Kirchengast to provide response to CGMS-40 request,	**Closed:** Text was provided right after IROWG-2 meeting and is part of CGMS-

documenting the LEO-LEO Essential Climate Variables (ECVs) capabilities.	40 EUM-WP-03 document.
Action IROWG2-08: Geoff Crowley and Gary Bust will lead workshops at CEDAR relevant to radio occultation. Tiger Liu and S. Y. Su will initiate radio occultation topics at upcoming IRI workshops.	**Closed.** Workshops were held at CEDAR consistent with the goals of this sub-group. Reports of the workshops are planned for IROWG-4 (action IROWG3-03).
Action IROWG2-09: Anthony Mannucci will distribute WMO information to the Space Weather sub-group according to sub-group recommendation 4.	**Closed.** On April 11-13 2012, two WMO documents relevant to space weather were distributed to the sub-group: “Implementation Plan For The Evolution Of Global Observing Systems (EGOS-IP)” in draft form, now available as WIGOS Technical Report No. 2013–4; and “Review Of Statements Of Guidance, Space Weather” WMO CBS/OPAG-IOS/ET-EGOS-7/ Doc. 8.3.2(15).

The open actions from all the workshops are collected below.

Action IROWG2-01: On IROWG co-chairs to contact the ITWG and survey the common interests between the groups.
Action IROWG2-02: Josep Aparicio will undertake a review to estimate both the total number of radio occultation measurements and the number of operational measurements available per day, based upon the current timeline of GNSS. This will allow us to foresee problems in data coverage in the coming years. An example is the data gap between COSMIC-1 and COSMIC-2; as there is a distinct possibility of no COSMIC-1 data by 2014.
Action IROWG2-05: On IROWG co-chairs and B. Ho, A. Steiner: Provide the following ROTrends information on the IROWG homepage: (a) Links to processing descriptions of all data providers; (b) Published ROTrends intercomparison papers; (c) ROTrends PPC and MMC datasets (including sampling errors of the latter).
Action IROWG3-01: NWP sub-group will compile a table of current Metop-B standard latencies (50 and 90% latencies, after processing, ready for delivery). Future operational missions should take that table as standard requirement (incl. COSMIC-2).
Action IROWG3-02: IROWG co-chairs to check progress towards updated laboratory measurements of the refractivity coefficients.
Action IROWG3-03: J. Y. Liu and Tony Mannucci will each provide a report on the activities at CEDAR that were initiated by Gary Bust and Geoff Crowley as part of Action IROWG2-08. J. Y. Liu will report RO related activities at the IRI conference in Olsztyn, Poland (June 2013). Due: IROWG-4.
Action IROWG3-04: Obtain information regarding access to COSMIC-2 data downlinks

globally to decrease data latency (objective is 30 minutes or less). Tony Mannucci will contact Paul Straus of Aerospace Corp to obtain information from the USAF. J. Y. Liu will contact NSPO to obtain information from that organization. Due: IROWG-4.
Action IROWG3-05: Sun Yue-Qiang of the Space Weather Sub-group will provide information on the planned use of FY-3C ionospheric data, including its use in space weather models. Due: IROWG-4.
Action IROWG3-06: All IROWG members to check and to provide feedback on the information given in the WMO Observing Systems Capability Analysis and Review Tool OSCAR: http://www.wmo-sat.info/oscar/. Due: ongoing.